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STUDY OF THE ENERGY ADDITION PROCESS
IN A D-C ARC-JET

R. J. Bryson and J. P. Fröhlich

ARO, Inc.

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ROCKET TEST FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
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NOTICES

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FOREWORD

The work reported herein was sponsored by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 61445014, Project 8951, Task 895105.

The research was conducted by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), contract operator of the AEDC under Contract AF 40(600)-1200. The work was conducted under ARO Project Number RW3501 in the Propulsion Research Area (R-2A-5) of the Rocket Test Facility (RTF), and the report was submitted by the authors as partial results of these research efforts on November 24, 1965.

The authors wish to acknowledge many helpful discussions held with W. K. McGregor, ARO, Inc., during the course of this investigation. Also the help of C. E. Redman, ARO, Inc., in developing the force measuring system is greatly appreciated.

This technical report has been reviewed and is approved.

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ABSTRACT

The thrust produced by a d-c arc-jet plasma generator operating with argon was measured and used to determine the division of the energy added to the gas between that which produced excitation and ionization and that which served to increase the translational energy of the gas. Energy division predicted by the Rayleigh heat addition theory was compared with the experimental determination and was found to be in fair agreement (15 to 30 percent). The plasma generator was operated at electrical power inputs ranging from 1.9 to 3.8 kw. Energy losses to the electrodes amounted to about 30 percent, so that about 70 percent of the total electrical energy input was actually added to the gas. The amounts of energy added to the gas ranged from 220 to 440 Btu/lb$_m$ at an argon flow rate of 0.00527 lb$_m$/sec. On the average, only about 40 percent of this energy addition was utilized to increase the total translational energy of the gas, and the remainder served to produce electronic excitation and ionization.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

A	Cross-sectional area of anode
a	Sonic velocity
c_p	Specific heat at constant pressure
F	Thrust
F_i	Ideal thrust
M	Mach number
m	Mass of an argon atom
$\dot{m}$	Mass flow rate
p	Static pressure
p_0	Total pressure
Q_E	Electrical energy supplied to generator
Q_{ei}	Energy available for excitation and ionization
Q_G	Energy added to gas
Q_{tr}	Total translational energy addition
Q_{tr_i}	Ideal translational energy addition
Q^*	Energy added which produces choked flow
R	Specific gas constant
T	Static temperature
T_0	Total temperature
V_i	Ionization potential
v	Velocity
α	Degree of ionization
γ	Ratio of specific heats
ρ	Density

SUBSCRIPTS

1	Station 1 at entrance to anode throat section
cell	Test cell conditions

SECTION I
INTRODUCTION

Arc-jet plasma generators have been used extensively during the past several years for hypervelocity, low-density, wind tunnels, as thrustors for space propulsion, and in other applications where a high enthalpy gas is required. Design of such devices requires a knowledge of the division of energy added in different forms, i.e., thermal and kinetic energy, electronic excitation and ionization energy, and also for polyatomic gases, the rotational, vibrational, dissociational energy. Generally such knowledge is not available because the energy addition mechanism is a very complex process accompanied by electron temperatures much in excess of gas temperatures (Ref. 1). The objective of the work reported here was to experimentally determine the energy addition in the translational mode (thermal and directed kinetic energy) of a monatomic gas, and thus distinguish it from the energy producing excitation and ionization.

The study was conducted in the Gas Kinetics Laboratory of the Rocket Test Facility, using a small arc-jet plasma generator with a constant area throat anode, and operating in a vacuum test cell, R-2A-5b, using argon as the working fluid. The total amount of energy absorbed by the gas was determined from an energy balance on the entire apparatus. The thrust produced by the generator is related to the energy addition required to produce choked flow. If the degree of ionization of the gas is small enough so that the heat capacities are unaffected by it, then the energy addition which produces choked flow is identical to the energy added to the gas in the total translational mode. The energy producing excitation and ionization does not contribute to the thrust under these conditions. It was therefore possible to determine the amount of energy addition in the translational mode by measuring the thrust produced by the generator. The difference between the total energy added to the gas and the total translational energy addition then represents the amount of energy available for excitation and ionization.

Experimental values of thrust produced by the generator were obtained over a limited range of energy additions at a constant gas flow rate. On the average, about 70 percent of the electrical energy supplied to the generator was absorbed by the gas. The fraction of the total energy added to the gas available for excitation and ionization was found to be, on the average, about 60 percent, corresponding to overall degrees of ionization of up to 2 percent, under the assumption that all this energy produces ionization.

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SECTION II
APPARATUS AND PROCEDURE

The experimental apparatus consisted of a low-pressure test cell, an arc-jet plasma generator, the necessary instrumentation for measurement of generator operating conditions, and a force measuring system to measure the thrust.

2.1 TEST CELL

The low-pressure test cell (Fig. 1) is a vertically mounted section of 30-in.-diam cylindrical pipe closed on one end and connected to a pumping system on the other. The pumping systems available are mechanical vacuum pumps, which can maintain the cell at approximately 2 mm Hg with secondary flow of approximately 0.0050 lb_m/sec, and the RTF exhaust system in conjunction with an air ejector, which can operate the cell at approximately 0.5 mm Hg with a similar secondary flow.

2.2 ARC-JET PLASMA GENERATOR AND INSTRUMENTATION

The arc-jet plasma generator used is of the Gerdien type and is shown in Fig. 2. The front and back plates are made of brass, and the main body is made of a ceramic electrical insulator. The rear plate contains a pressure sealed opening for the cathode, a tap for measuring the chamber pressure, and a gas supply opening. Gas is introduced through a perforated plate to ensure uniform distribution around the chamber. The front plate is provided with a water-cooled jacket into which replaceable copper anodes may be inserted. The cathode assembly consists of two concentric tubes, with cooling water flowing through the annulus, and a copper heat sink threaded on the end into which the tungsten cathode material is force fitted. The cathode assembly may be moved axially to provide different arc gaps. The following parameters were measured:

Gas supply pressure	0- to 200-in. HgA Bourdon gage
Gas flow rate	0- to 10-scfm Brooks rotameter
Gas inlet temperature	Hg thermometer
Generator chamber pressure	0- to 15-psia Bourdon gage
Arc voltage	Voltmeter
Arc current	Millivoltmeter and shunt

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Cooling water flow rate	Time required to fill a given volume
Cooling water inlet and outlet temperature	Dial thermometer
Cell pressure	McLeod gage

2.3 FORCE MEASURING SYSTEM

A rotating hollow shaft in the force measuring system transfers the force produced by the generator through the cell wall to the end of a small cantilever beam mounted outside the cell. A strain gage is attached to the cantilever beam to detect changes in beam deflection, and the output voltage is monitored on a recording potentiometer. The rotating shaft (Fig. 3) is made of a stainless steel tube with arms clamped on each end. The generator is mounted vertically on one arm, and the other is equipped with a Teflon® capped screw which bears on the end of the cantilever beam through a Teflon pad. The shaft rotates in bearings fitted into a larger tube which is welded to a plate to mount the assembly to the cell access port flange. The area between the shaft and tube is sealed with a Teflon O-ring. The generator instrumentation and supply leads are fed through the shaft to the outside, and the end of the shaft is capped to prevent leakage into the cell. This arrangement eliminates drag produced by the electrical leads and plumbing. To prevent axial motion of the shaft due to atmospheric pressure on the end when the cell pressure is reduced and to minimize frictional effects, a small steel pin is inserted between the end of the larger tube and the arm clamped on the outside of the shaft. This pin is free to move in any direction except along its axis.

2.4 PROCEDURE

Generator operating parameters for each operating condition are obtained by the following procedure. The generator is started, the desired gas flow rate and electrical energy input level are set, and the generator is allowed to operate until all transients have dissipated (about 5 min). At this point the previously mentioned parameters are recorded, and the position of the strain-gage potentiometer indicator is noted. The generator power and gas flow are then cut off, and the potentiometer position is again noted. The difference between the two positions is proportional to the thrust produced by the generator. After the desired number of generator operating conditions has been obtained, a thrust versus potentiometer position calibration is performed

by applying known weights to the generator and noting the potentiometer position. Since the strain gage is operated in the region of linear response, the calibration curve is a straight line, and its slope is the proportionality constant between generator thrust and potentiometer position. For each calibration, the indicator position for a given applied weight can be repeated within ±3 percent. The range of the thrust measuring apparatus is 0.01 to 5 lb$_f$.

To determine the portion of the electrical energy which is added to the gas, Q_G, an energy balance is performed on the generator. The amount of energy absorbed by the cooling water is determined from the water flow rate, its specific heat capacity, and the change in the water temperature. This energy is then subtracted from the input electrical energy, and the remaining amount is assumed to enter the gas. On a per pound of gas basis this appears in equation form as

$$Q_G = Q_E - \frac{(c_{p_w})(\dot{m}_w)(\Delta T_w)}{\dot{m}_g} \tag{1}$$

For these experiments, the gas flow rate was maintained as constant as possible (at 0.00527 lb$_m$/sec), and the electrical power input was varied from 1.9 to 3.8 kw. Argon gas was used exclusively as the working fluid, chamber pressures ranged from 7.58 to 9.20 psia, and a 0.250-in. constant diameter sonic nozzle anode was used. Q_G is presented as a function of Q_E in Fig. 4. (Each set of points represents data obtained during one continuous run.) This graph indicates that approximately 70 percent of the electrical energy supplied to the generator is absorbed by the gas.

SECTION III
ANALYSIS

It is observed experimentally that the plasma issuing from the generator is supersonic. This implies that the flow is choked somewhere in the anode throat as a result of the energy addition. Visual evidence indicates that in this generator very little energy, if any at all, is added to the gas downstream of the anode exit. This leads one to believe that the flow is choked very near the anode exit plane. These two conditions are used in this analysis along with the assumptions that the flow is one-dimensional as it passes through the sonic station, that the plasma behaves like an ideal gas, and that the mean degree of ionization is small so that the plasma may also be considered to behave like a calorically perfect gas. The validity of these assumptions will be analyzed in the light of the results.

The thrust produced by the generator, F, is given by

$$F = \dot{m} v^* + (p^* - p_{cell}) A \tag{2}$$

By using the mass flow equation,

$$\dot{m} = \rho^* v^* A \tag{3}$$

the equation of state,

$$p^* = \rho^* RT^* \tag{4}$$

the thermodynamic relationship,

$$c_p = \frac{\gamma}{\gamma - 1} R \tag{5}$$

the condition of choked flow,

$$v^* = Q^* = \sqrt{\gamma RT^*} \tag{6}$$

and the isentropic temperature relationship at the sonic throat,

$$T^* = \left(\frac{2}{\gamma + 1}\right) T_o^* \tag{7}$$

then the thrust produced by the plasma generator can be expressed as a function of the total temperature at the sonic throat and measured flow parameters in the form

$$F = \dot{m} \sqrt{2 \left(\frac{\gamma^2 - 1}{\gamma^2}\right)} \sqrt{c_p T_o^*} - p_{cell} A \tag{8}$$

The energy addition required to produce choked flow is

$$Q^* = c_p T_o^* - c_p T_{o_1} \tag{9}$$

where $c_p T_{o_1}$ is the total enthalpy of the gas upstream of the heating zone. Since this energy addition merely serves to increase the total temperature of the gas, it can be identified with the energy added in the form of total translational energy, Q_{tr} (i. e., the sum of thermal and directed kinetic energy). The thrust produced by the plasma generator is thus related to the energy addition in the translational mode by

$$F = \dot{m} \sqrt{2 \left(\frac{\gamma^2 - 1}{\gamma^2}\right)} \sqrt{Q_{tr} + c_p T_{o_1}} - p_{cell} A \tag{10}$$

Equation (10) is used in the calculation of Q_{tr} from the measured thrust for a given generator operating condition.

Under the assumption that all the energy, Q_G, is added to the gas upstream of the sonic throat, the amount of energy added in the form of excitation and ionization energy therefore is

$$Q_{ei} = Q_G - Q_{tr} \tag{11}$$

If the entire amount, Q_{ei}, produces ionization, the fraction of gas ionized will be

$$\alpha^* = \frac{m \, Q_{ei}}{V_1} \tag{12}$$

A calculation for a typical measured thrust of 0.4 lbf indicated a static temperature of 1150°R at the sonic station. Most ionization of the gas is thus not produced thermally, i.e., by collisions of the gas atoms with one another, but rather is produced by the direct inter-action of the arc with the gas. The maximum possible overall degree of ionization for this condition, as calculated from Eq. (12), is 1.2 per-cent. Thus, the assumption that the specific heat capacities remain very near the cold gas values is justified.

It is desirable to be able to predict the division of energy addition in the different modes simply from the generator operating conditions without an actual thrust measurement. A comparison was, therefore, made of the measured thrust and the ideal thrust that would be pro-duced by the plasma generator if there were no impulse losses in the anode flow region. This comparison is shown in Fig. 5. The ideal thrust is based on the momentum flux across the entrance plane of the heating zone rather than across the exit plane, and is, therefore, given by

$$F_1 = \dot{m} \, v_1 + (p_1 - p_{cell}) A \tag{13}$$

With the assumptions of local one-dimensional flow and perfect gas behavior, the ideal thrust can be expressed in terms of p_{01}, p_{cell}, A, and γ in the form

$$F_i = p_{o_1} A (1 + \gamma M_1^2) \left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{-\frac{\gamma}{\gamma - 1}} - p_{cell} A \tag{14}$$

where the Mach number at the anode entrance, M_1, is related to $\dot{m}$, A, p_{01}, and T_{01} by the following form of the mass flow equation (Ref. 2)

$$\frac{\dot{m}}{A} = \sqrt{\frac{\gamma}{R}} \frac{p_{o_1}}{\sqrt{T_{o_1}}} \frac{M_1}{\left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\frac{\gamma + 1}{2(\gamma - 1)}}} \tag{15}$$

Under the assumption that no energy is transferred to the gas by the electric arc upstream of the anode entrance, p_{01} and T_{01} correspond to the values in the generator chamber. Thus, Eqs. (14) and (15) combined give a relationship between the ideal thrust and the measured generator operating parameters $\dot{m}$, p_{o_m}, and T_{o_m}.

As can be seen from Fig. 5, the ideal thrust is consistently higher than the measured thrust. The difference in the thrusts represents the

loss of gas impulse from the entrance to the exit plane of the anode, which results from wall friction and the interaction of the applied electric field with charged particles of the plasma. Figure 5 shows that the loss of gas impulse is, on the average, only approximately 6 percent of the ideal thrust. A relatively good estimate of the division of the energy addition, without an actual thrust measurement, can thus be obtained by considering the flow in the anode region to experience no impulse loss. Under this condition, the ideal translational energy addition is determined from Eq. (10) based on the ideal thrust, namely

$$Q_{tr_i} + c_p T_{o_1} = \frac{(F_i + p_{cell} A)^2}{2 \dot{m}^2 \left(\frac{\gamma^2 - 1}{\gamma^2}\right)} \tag{16}$$

The ideal energy addition in the translational mode is then related to the generator operating parameters, since from Eqs. (5), (14), (15), and (16),

$$\frac{Q_{tr_1} + c_p T_{o_1}}{c_p T_{o_1}} = \frac{(1 + \gamma M_1^2)^2}{2 (\gamma + 1) M_1^2 \left(1 + \frac{\gamma - 1}{2} M_1^2\right)} \tag{17}$$

where M_1 is related to the operating parameters by Eq. (15). Under this ideal condition the energy addition in the translational mode is therefore predicted by a Rayleigh heating process since Eq. (17) represents the ratio of the final to the initial total temperature for a Rayleigh heating process (Ref. 2). The amount of energy added to the gas in the translational mode for the ideal situation, Q_{tr_i}, is compared with the actual energy addition, Q_{tr}, in Fig. 6. The resulting degrees of ionization, as determined from Eqs. (11) and (12), are shown in Fig. 7 corresponding to the measured and the ideal conditions.

SECTION IV
DISCUSSION

As can be seen in Fig. 5, there is some scatter in the experimental results. The method employed to determine generator chamber conditions and thrust values involved a time lapse of approximately a minute and a half between initiation and completion of the data acquisition cycle. At times the generator operating conditions would change slightly over this period and required resetting. These changes were more pronounced at the higher powers, and it is felt that such changes which were not detected were responsible for the small scatter.

Uniformity of gas properties in the entrance and exit planes of the anode throat is contained in the assumptions. In a generator of similar

design, it was found by Dooley, et al. (Ref. 3), that the arc in argon is of a random, high frequency nature. This could cause the energy addition process to be of an averaging nature, so that uniformity of gas properties might actually exist.

In the results, the maximum amount of overall ionization attainable is calculated by assuming that all energy available for excitation and ionization produces ionization. The resulting degree of ionization, which is on the order of one percent, is therefore somewhat overestimated. Saha's equation (Ref. 4), based on gas temperature, indicates that a negligible percentage of the gas would be ionized. Saha's equation, based on a typical electron temperature of 15,000°K as obtained by spectroscopic measurements (Refs. 1 and 5), predicts that approximately 40 percent of the gas should be ionized. Therefore, the actual ionization process cannot be described by the equilibrium ionization equation at either of these temperatures. This is also intuitively expected since it was shown that most ionization results from the direct interaction of the arc column and the gas.

SECTION V
CONCLUDING REMARKS

The experimental evidence indicates that, in this plasma generator, a relatively large portion of the energy addition is available for electronic excitation and ionization. But even if one assumes this entire amount of energy to produce solely ionization, the fraction of the gas that is ionized is nevertheless quite small. The amounts of thrust produced by the plasma generator further indicate that the mean gas temperature at the generator exit, and thus throughout the heating zone, is considerably less than the temperature that is required for thermal ionization. This leads one to believe that most ionization is produced by the direct interaction of the arc column with the gas. The electric arc can thus be considered as a heating element which independently raises the gas total temperature and excites and partially ionizes the gas. Conventional gas dynamic theory should, therefore, give a fair approximation for the mean plasma properties if the degree of ionization is small, whereas an energy balance on the plasma generator will determine the amount of excitation and ionization.

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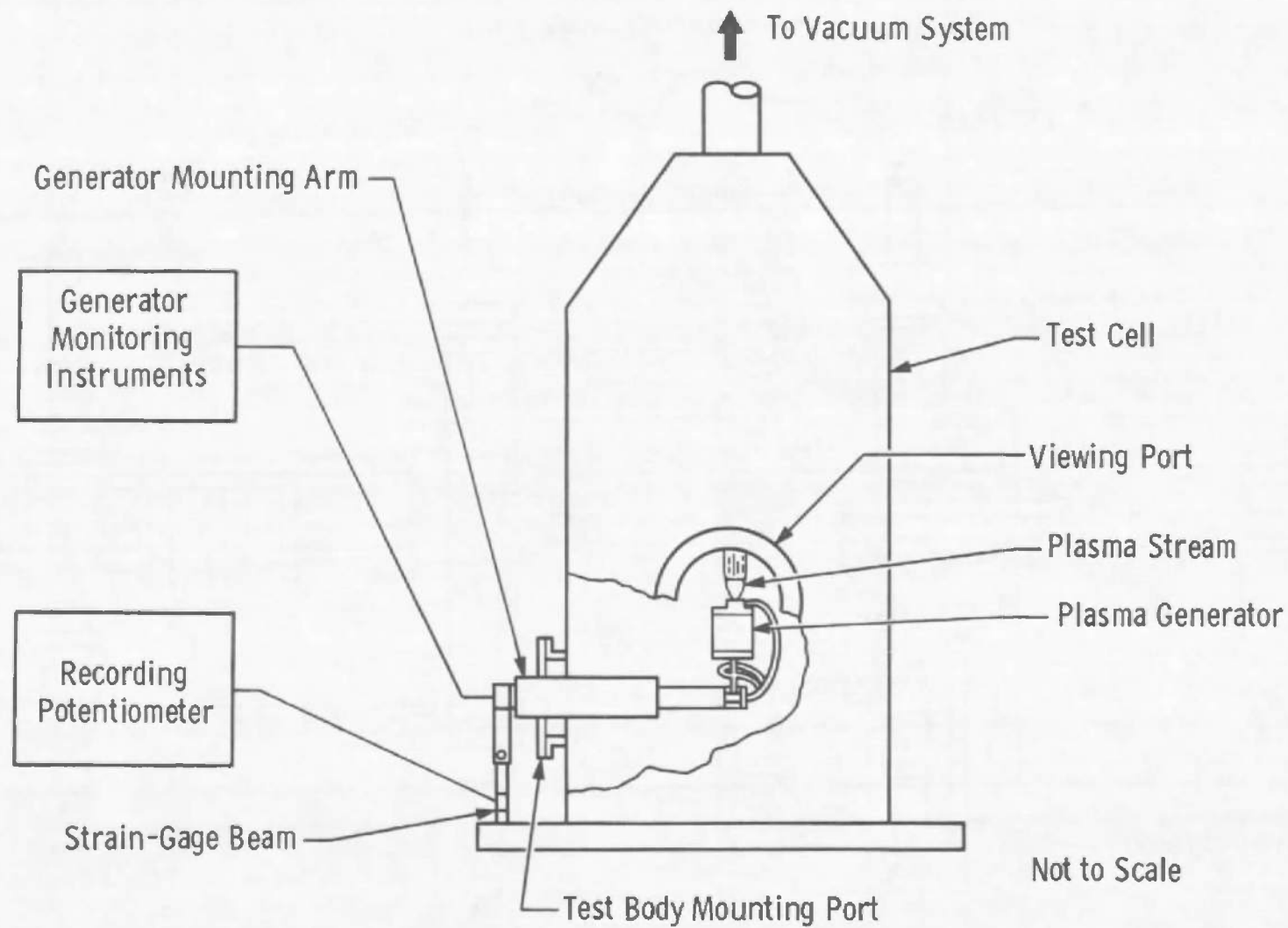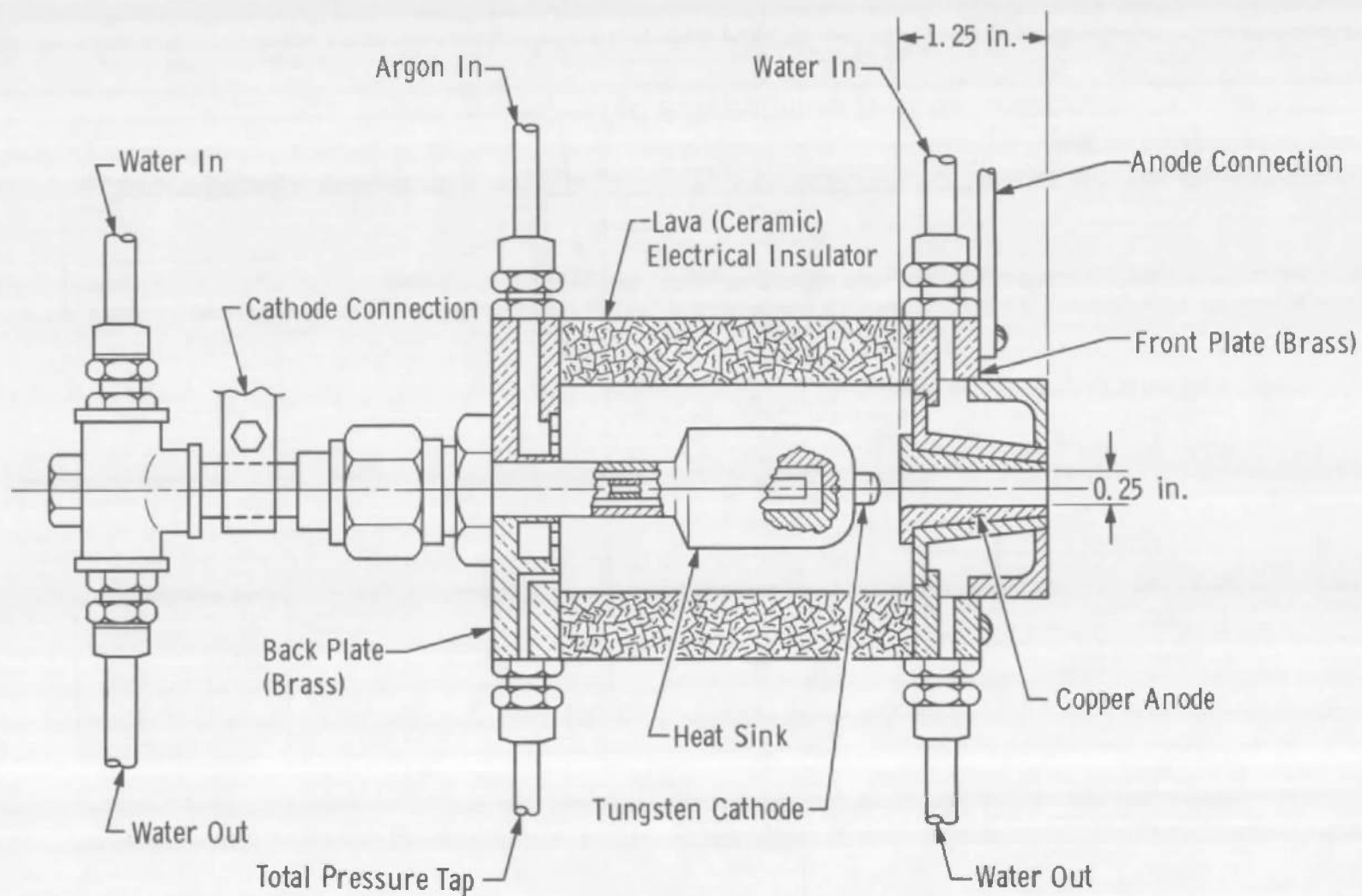
To Vacuum System

Generator Mounting Arm

Generator
Monitoring
Instruments

Test Cell

Viewing Port

Plasma Stream

Plasma Generator

Recording
Potentiometer

Strain-Gage Beam

Not to Scale

Test Body Mounting Port

Fig. 1 Test Cell
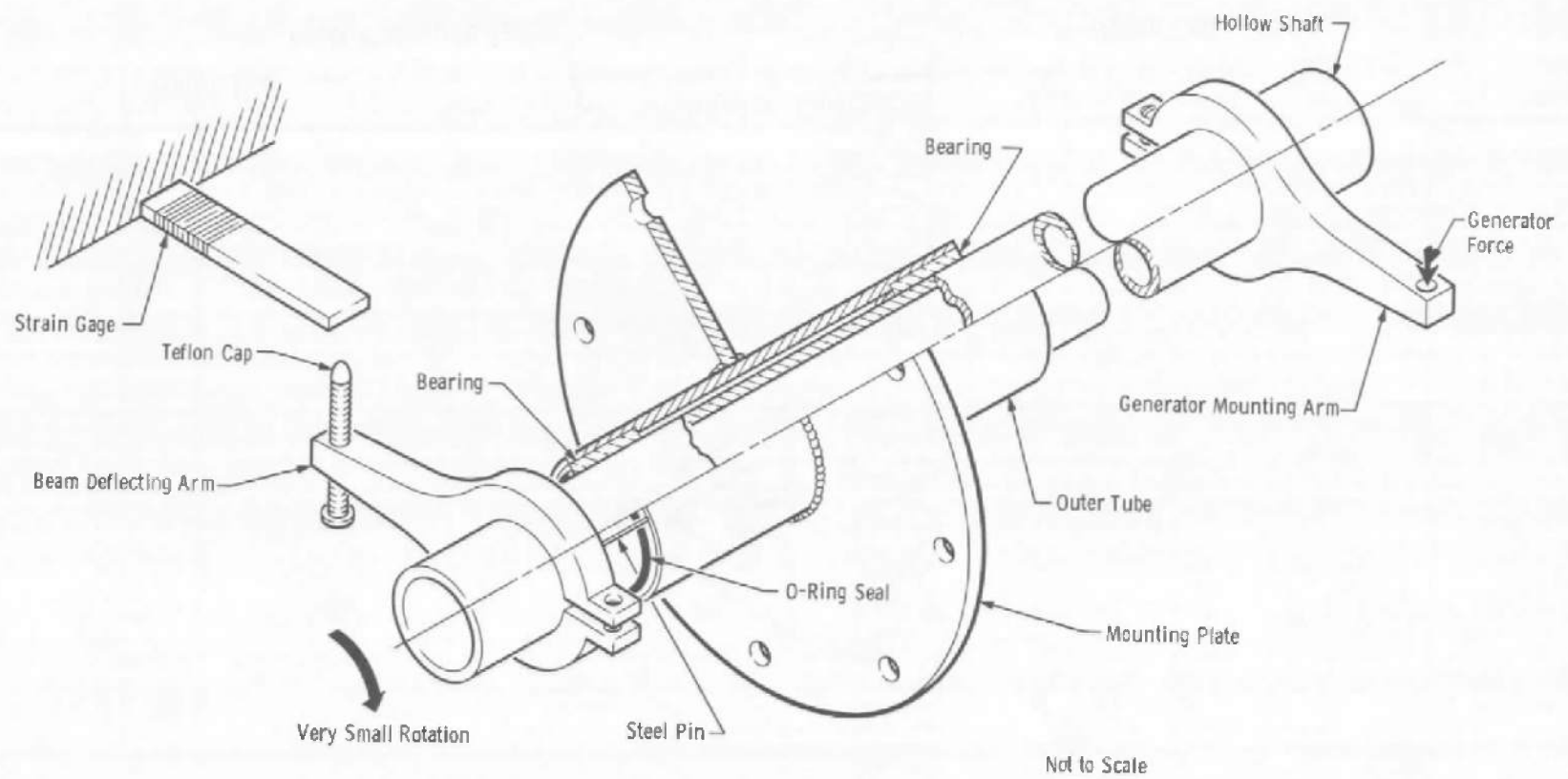
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Fig. 2 Arc-Jet Plasma Generator
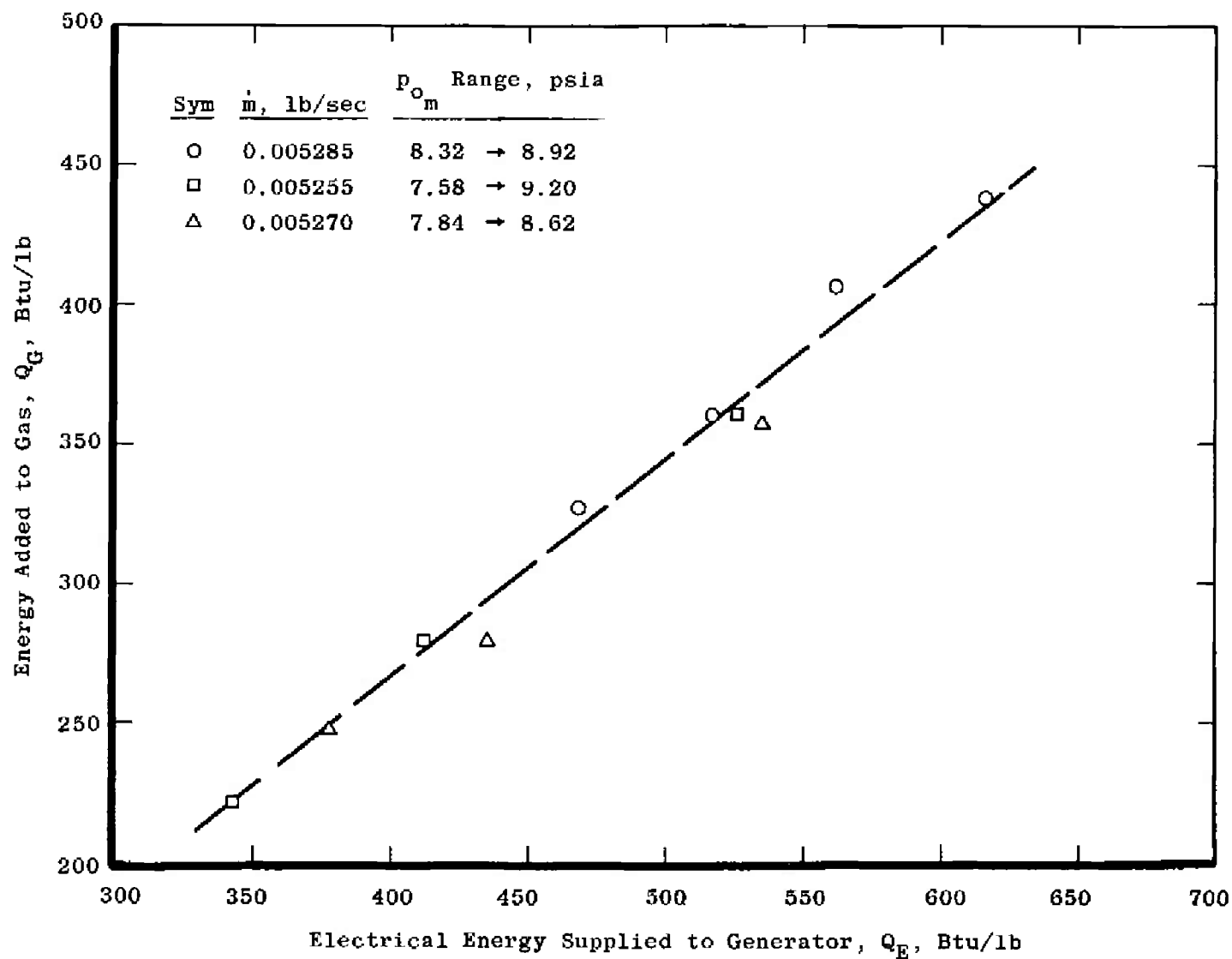
Fig. 3 Generator Support Arm

Not to Scale

Fig. 4 Variation of the Energy Added to the Gas with Electrical Energy Supplied to the Generator
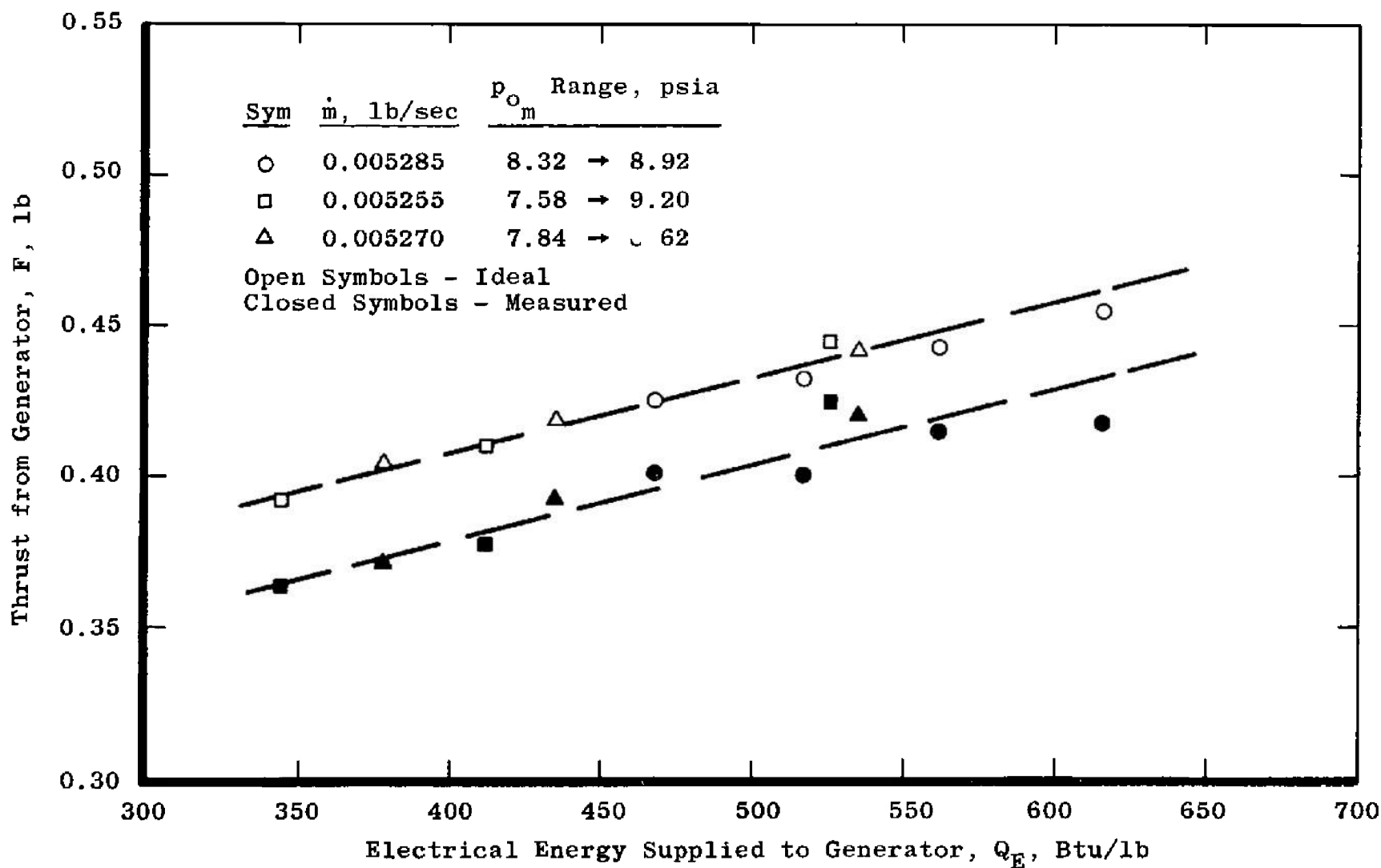
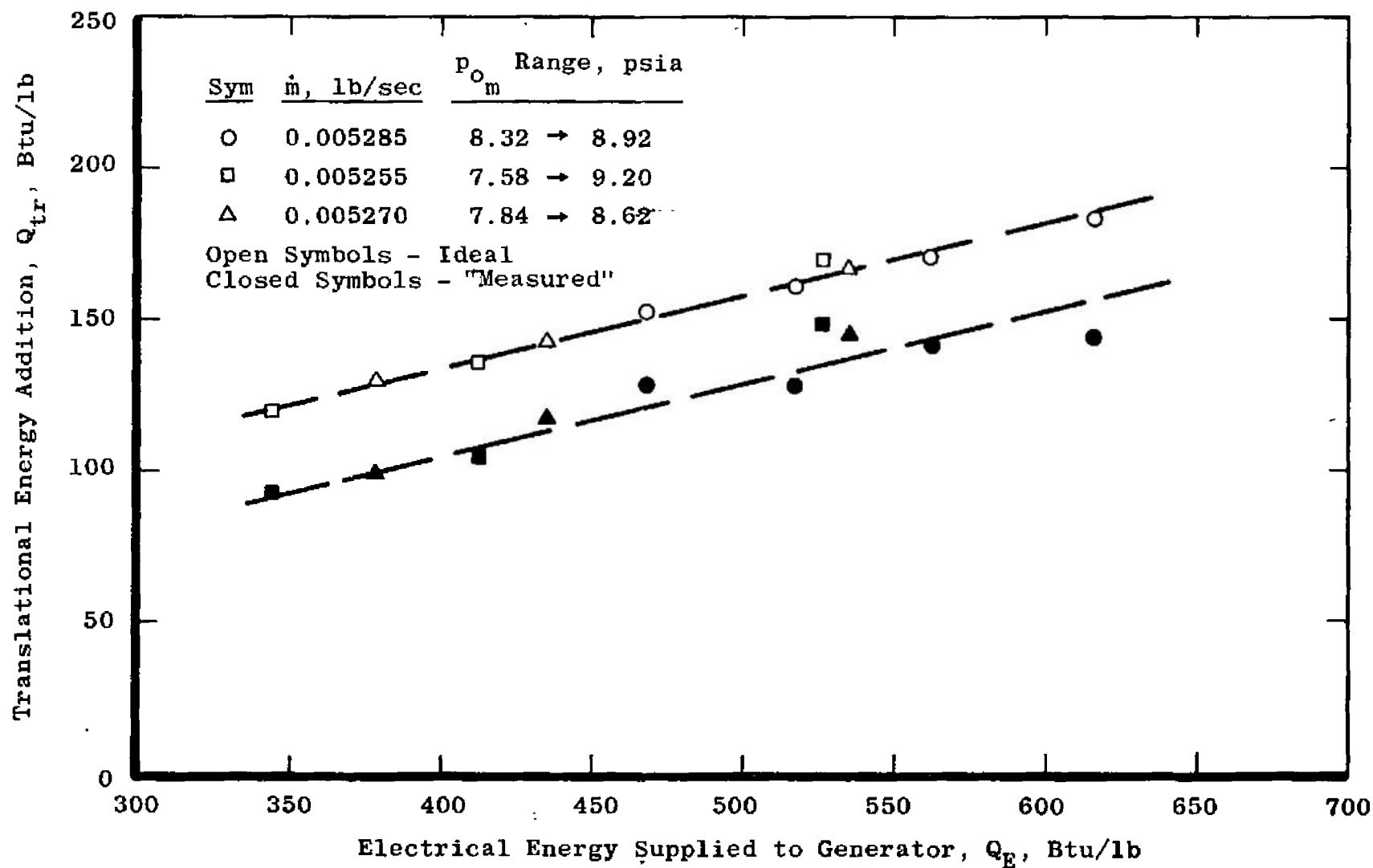Fig. 5 Comparison of Ideal and Measured Thrusts

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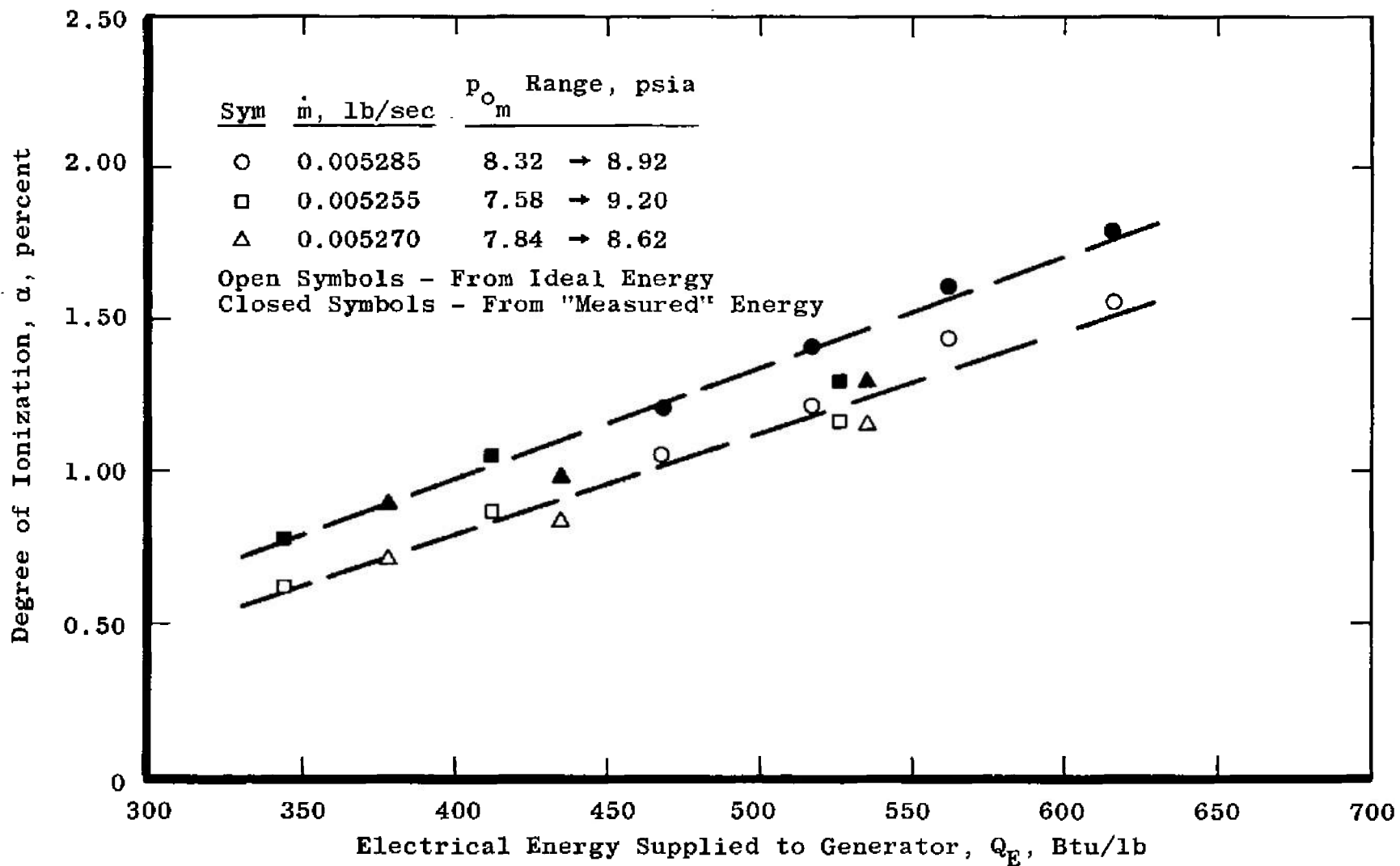Fig. 6 Comparison of Ideal and "Measured" Translational Energy Additions

Fig. 7 Effect of the Electrical Energy Supplied to the Plasma Generator on the Degree of Ionization Produced at the Sonic Station

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13 ABSTRACT

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